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Compact Gas and Aerosol Sensing based on Photothermal Interferometry

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Summary:
An instrument for gas and aerosol sensing based on photothermal interferometry has been developed. Depending on the light source used for photothermal excitation, either gas or aerosol concentrations may be measured. A fabrication process for low-cost air-spaced Fabry-Pérot etalons, for the interferometric detection unit, is presented. Based on a demonstrator setup, an extensive scrutiny of all noise sources is being performed serving as a basis for the evaluation of the miniaturization potential of said sensor system. First measurements with water vapor were conducted, highlighting the sensor's potential.

Keywords: Photothermal Spectroscopy, Photothermal Interferometry, Fabry-Pérot Etalon, Gas Sensing, Aerosol Sensing

Introduction

Photothermal interferometry (PTI) has received a lot of scientific attention in recent years, due to outstanding sensitivities and selectivity. In PTI the target gas is periodically excited via laser irradiation, leading to a modulated local heating and, therefore, to a modulated change of the refractive index (RI). This change of RI can be detected interferometrically, e.g. by the use of a Fabry-Pérot etalon (FPE), allowing miniaturization, as the laser-gas interaction path can be reduced drastically. However, in the past, mostly complex and large bench-top systems have been developed [1]. It has also been shown, that a commercial all-optical microphone can be utilized for the detection of photothermal signals [2], with the downside of high costs. In order to demonstrate compact, reliable and efficient systems compatible with large-scale production, all components have to be evaluated with regard to miniaturization potential, noise contributions and cost. Selective and reliable measurement of gases like CO/CO_2 will greatly benefit areas like medical health monitoring (breath analysis), the automotive industry (cabin sensing), and environmental monitoring (greenhouse gases).

Methods

For the systematic analysis of all signal-limiting noise sources, a system model and a lab demonstrator have been developed and built. The setup is depicted in Fig. 1. The interferometer's light source (probe laser) is an ultra-low-noise (ULN) laser with exceptionally narrow linewidth (<100 *Hz*) and is controlled with the provided software. An isolator prevents back-reflections into the laser cavity and the subsequent 90/10 splitter divides the light into a signal- and a reference path, allowing the use of a balanced photodetector (BD). Thereby, common noise present in both light paths is electronically canceled, allowing measurements at the shot noise limit. Due to the FPE being present in just the signal path, laser phase noise, which gets converted by the FPE into amplitude noise, cannot be eliminated by the BD, highlighting the need for an ULN laser.

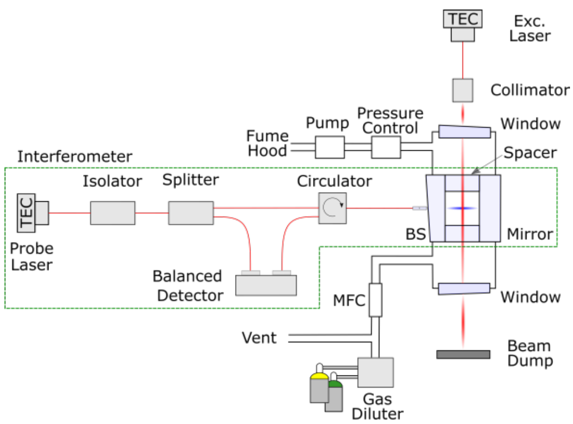

Fig. 1. Schematic of the optical PTI setup. The green frame indicates the interferometer. Fibers = solid red lines, free space excitation laser light = red beams, probe laser = blue beam, BS = beamsplitter, MFC = mass flow controller, TEC = thermo electric cooler.

Roughly 10 % of the light from the splitter is guided onto the reference photodiode of the BD and the rest is directed into the FPE via a circulator. The light reflected from the FPE is transmitted to the signal photodetector of the BD. As the system should be compact, rugged and low in cost, a custom-made air-spaced FPE is used as an interferometer. The FPE was built completely by standard, commercially available bulk-, as well as fiber-optic components. It is integrated into a gas-tight 3D-printed measurement cell. The bulk optic etalon consists of a 70 % semi-reflecting, as well as a highly-reflecting mirror, which are separated by 3 mm high-precision spacers. To maintain optical alignment during handling, the etalon is fiber-coupled via a GRIN lens, permanently mounted onto the backside of the semi-reflecting mirror. An alignment platform, consisting of translation and goniometric stages was assembled, to optimize the coupling between the fiber-coupled GRIN-lens collimator and the etalon. To maximize sensitivity, the operating point (OP) of the FPE has to be tuned to the inflection point of the reflectance function, where its first derivative has a maximum. For proof of principle measurements, the laser's wavelength is fixed at the OP via a constant driving current. Further, feedback-based, stabilization methods are subject of ongoing work. Water vapor was chosen for initial tests, as its strong absorption bands (e.g. at 1364.7 nm) can be targeted with low-cost telecom laser sources. Via a lens, the excitation laser is focused through the measurement cell, intersecting the probe beam perpendicularly inside the FPE. System control and data acquisition are implemented on a National Instruments FPGA-based system. The modulation frequency was set to be 125 Hz, well clear of disturbing 50 Hz harmonics.

Results

With the alignment setup, as well as the optical components described in the previous section, a fiber-coupled FPE with an effective finesse of ~15 could be fabricated and characterized. In Fig. 2, a rendering of the measurement cell with integrated FPE as well as the measured reflectance function is depicted.

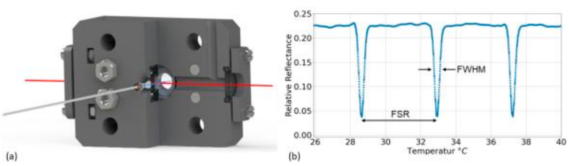

Fig. 2. The fiber-coupled bulk-optical FPE. (a) Rendering of the measurement cell with the integrated FPE. Red lines = excitation, blue lines = probe laser. (b) Temperature sweep over three free spectral ranges (FSR), with arrows indicating the full width at half maximum (FWHM).

For water vapor measurements, the cell is operated with open windows and exposed to ambient air with a concentration of 13 762 ppmV, as measured by a reference device (temperature = 21.4°C, pressure = 979.9 hPa, relative humidity = 52.2 %). The signal is extracted by means of a Fast Fourier Transform (FFT) and compared to the background signal with the excitation laser turned off (see Fig. 3). A signal to noise ratio (SNR) of more than 7000 can be obtained, corresponding to a limit of detection of approximately 5 ppmV (3σ).

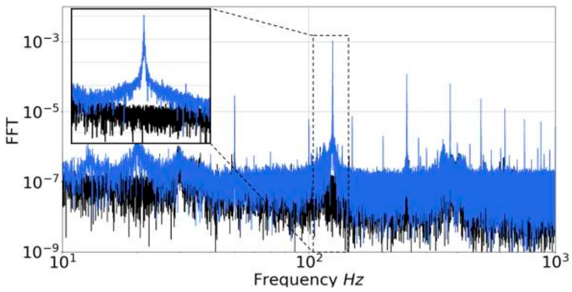

Fig. 3. FFT signal of two measurements. In blue, the modulated (125 Hz) excitation laser is turned on. The first (inset), as well as higher harmonics can clearly be distinguished from the background. In black, the background, with the excitation laser turned off, is shown.

Additional use of a Lock-In amplifier is expected to further increase the SNR.

Conclusion and Outlook

We have successfully developed and built a PTI system from ground up. A novel method to fabricate a low-cost air-spaced FPE from standard commercially available components has been established. First proof of principle experiments with water vapor were conducted and a SNR of more than 7000, for 13 762 ppmV, has been achieved. A custom developed ICL laser source in the 4 µm region [3] will be implemented as excitation source, enabling sensitive measurement of greenhouse gases like CO_2 at compact overall system sizes. Further optimization of the sensor system is in progress and is expected to improve performance significantly.

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